A Comprehensive Investigation of the Electrical Features of Commercial Resistive Flex Sensors

Giovanni Saggio
Dept. Electronic Engineering
University of Rome "Tor Vergata"
Rome, Italy
saggio@uniroma2.it

***Abstract*— Resistive flex sensors have been gaining more and more importance in the latest years. They are applied in many and different fields ranging from human body tracking, traffic safety, musical instruments and so on. These sensors have the mechanical advantage to be low-weight, unobtrusive and pliable. However from an electrical point of view different works have been devoted to investigate single properties, but there is a lack of a comprehensive investigation, useful to select the proper sensor for the proper application. This paper is devoted to fill this lack.**

Keywords-resistive flex sensor; bend sensor.

I. Introduction

A Resistive Flex Sensor (RFS hereafter) consists typically of a thin flexible substrate painted on-top with a polymer ink, which includes conductive particles moved apart when the sensor is bent away (outward) from the ink. Because of the distances of the particles, an outward bending produces an increasing of the RFS impedance, which was demonstrated to be substantially resistive (real), since the reactive (imaginary) part is practically negligible [1]. The change in resistance is fully reversible; so that the sensor returns to its initial value when straighten.

RFSs are furnished without or with a protective coating layer, useful for chemical/mechanical protection when necessary. In the first occurrence RFSs are known as uncoated (or base, or bare), otherwise as coated (or over-laminated). Regarding all the different technological material and procedures in developing RFSs, the interested reader can find a comprehensive review in [2].

RFSs having only one layer printed with the conductive ink do not usefully respond when bent in the opposite side (inward) from the ink. Only the two-layer engineered types can respond both increasing and decreasing their resistance with both outward and inward mechanical bending.

In the latest years, RFSs have been widely adopted for different purposes. Examples are bio-metrics (placement or movement of patients/athletes) [3], robotics (in realizing position feedback mechanism) [4], virtual-reality (user equipped with a sensory glove integrating RFSs virtually interact with objects on a PC screen) [5], automotive (for car occupant or traffic safety) [6] [7], musical instruments (transforming common gestures into sound creation) [8], assistive technologies (for communication of speechless users) [9], and so on.

Despite their widespread usage, as far as we know, only single electrical issues of RFS have been treated in single papers, and some features have not been treated at all. This paper is aimed to fill this lack.

In particular, our investigation of the electrical features of commercial RFSs considers the electrical resistance R versus angle of bending α (expressed as $R=R(\alpha)$), the overall electrical variation ΔR, the sensitivity $S=\Delta R/\Delta\alpha$, the repeatability, the hysteresis and the step response decay. In addition, all these aspects are here analyzed with respect to the RFS bending around pivots of different radiuses (0.6cm, 0.8cm, 1.0cm, 1.2cm), RFS differently over-laminated (none, polyester, polyamide), with different length (1", 2", 3", 4.5"), and with inward (-90° to 0°) and outward bending (0° to 120°).

In principle, RFSs can be indigenously prepared for custom design (an example explained in [10], but our investigation focuses on the mostly used RFSs, which are commercialized by Flexpoint (FP hereafter, www.flexpoint.com) and Spectrasymbol (SS hereafter, www.spectrasymbol.com), in particular the one-layer engineered types (also known as *unipolar*) being the most adopted ones.

Section II reports details about the RFSs we adopted and the designed set-up used to characterize them.

Section III is devoted to the outputs of the measurements and the resulting comments and suggestions useful for the selection of the right sensor for the right application.

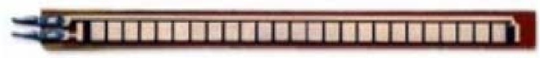
Section IV concludes with some remarks.

II. Materials and Methods

RFSs by FP come in one uncoated version and in two coated versions (realized by means of polyester and polyamide respectively) and in three lengths of 1", 2" and 3" respectively (Figure 1a). As a peculiarity, the SS RFSs are born with an inner high resistance of their conductive ink (in the MOhm range), so that some metallic pads are added (Figure 1b) to lower this high-value resistance to more convenient values.

 ISBN: 978-1-61208-523-4

(a)



(b)

Figure 1. (a) FP RFSs with different length of 1”, 2”, 3” and (b) SS 4.5’’ lenght RFS with additional metal pads visible on-top (at bottom).

The SS manufacturer does not provide any information regarding an eventual coating layer.

Table 1 summarizes the different types of RFSs under tests. Differences are in manufacturer, over-lamination and length.

TABLE I. DIFFERENT TYPES OF RFSS USED FOR OUR TESTS

Flexpoint		
Code	***Overlamination***	***Lenght***
A15, B11, G6, H6, H15, I15, I17	none	2”
A17, C15, I12	polyamide	2”
B10, D11, F16	none	3”
C1, C14	polyester	3”
C5, H11, N7	none	1”
E3	polyamide	3”
G5, G14, J4	polyester	2”
SpectraSymbol		
S1, S2, S3, S4, S5, S6, S7	unknown	4.5”

The electrical features of the RFSs were obtained by means of a fully automatized set-up, so to overcome, as far as possible, human subjected errors. The core of the set-up was a mechanical hinge, with one leaf fixed on an anti-vibrating bench, and one leaf welded to a central cylindrical pin and rotating with it. The rotation was obtained by means of a stepper motor (PD-109-57 by Trinamic, Hamburg, Germany). Each RFS was laid along the hinge so to bend according to the rotation of the mobile leaf (Figure 2). Four different hinges were utilized, with different diameters of the pin, 0.6, 0.8, 1.0 and 1.2cm respectively.

Data were acquired by means of a multimeter (Agilent 34405, by Agilent, Santa Clara, CA, USA), and the overall system was controlled via LabVIEW routines (Laboratory Virtual Instrumentation Engineering Workbench, by National Instruments, Austin, TX, USA). The ad-hoc realized LabVIEW graphical interface consisted of different sections with commands devoted to set/acquire data from the motor and the multimeter (Figure 3).

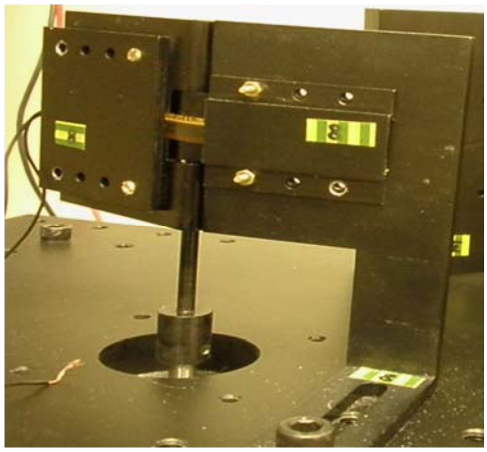


Figure 2. The RFS lies on a hinge having one leaf rotated by means of a stepper motor (not visible in the figure)

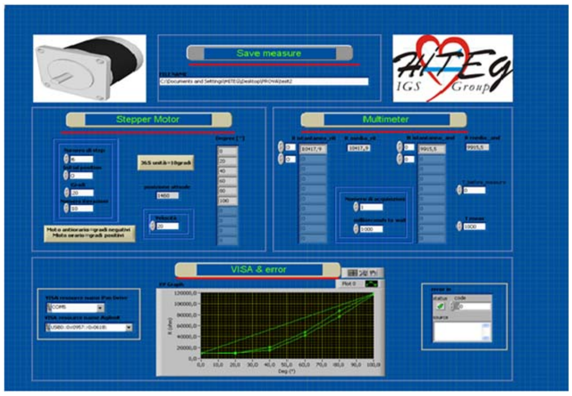


Figure 3. The graphical interface useful to control instruments and to acquire data from the sensors

All tests were performed in a room with fixed and controlled temperature (20°C) and humidity (40%).

Each RFS was tested bending it from 0° to -90° to 0° (inward “round trip” bending) and from 0° to 120° to 0° (outward “round trip” bending), each cycle (“trip”) ten times iterated. The mobile leaf was rotated at 20 degree/sec, and paused every 5° to allow 10 data averaged acquisition during 500ms. For the “step response decay” test, each RFS was simply randomly flexed and then returned to the flat position maintained for 60min, during which data were continuously acquired.

III. RESULTS AND DISCUSSION

A. R vs. α

Let us start considering the RFS electrical behavior in terms of resistance R versus bending angle α, “R vs. α”.

Figure 4(a) shows how sensors of the same type and length offer a different interval of resistance even when bent by the same amount, which seems to indicate the necessity to measure all RFSs, one-by-one, before their adoption. However, Figure 4(b) evidences a common trend for all the sensors with normalizing resistance data to 0-1 range. In

ISBN: 978-1-61208-523-4

particular, for simplification purposes, if we can accept roughly a 12% of maximum error, we can adopt a unique average curve for all the sensors, as evidenced in Figure 5.

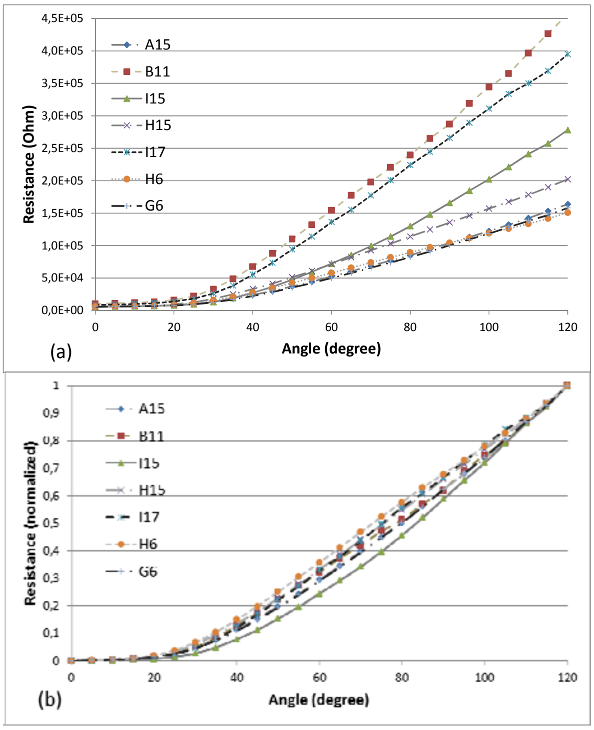


Figure 4. *R* vs. α (a) one-by-one and (b) normalized curve of uncoated FP RFSs

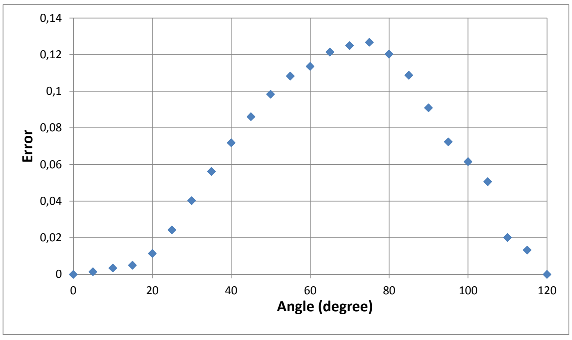


Figure 5. The maximum differences in resistance between normalized curves at each agle of bending for the ncoated FP RFSs

Similarly, the FP polyamide-coated and polyester-coated samples demonstrated different "*R* vs. α" curves (Figure 6a, b), but all with a similar trend, highlighted when a comparison is performed among the normalized versions of the curves.

We interpolated all the previous "*R* vs. α" curves using the "polyfit" function of Matlab (by MathWorks®, Inc.), that is a polynomial fitting, with the related fit error evaluated in terms of "residuals" (differences between the response data and the fit to the response data).

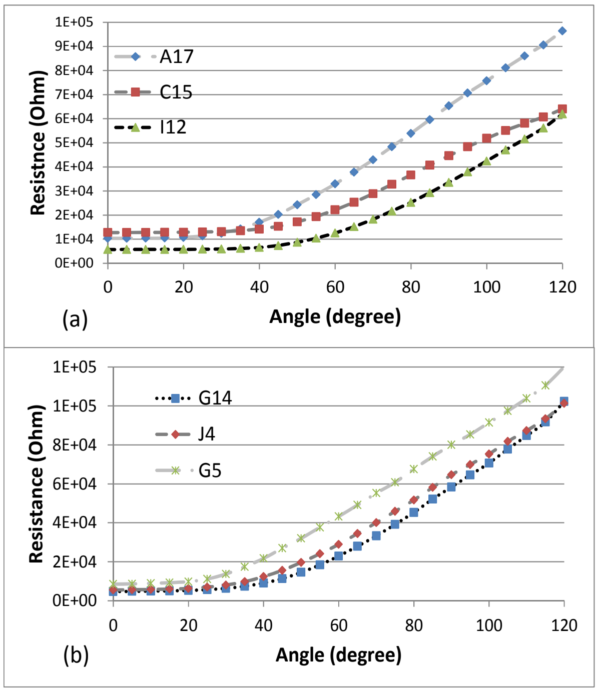


Figure 6. *R* vs. α curves for FP (a) polyamide and (b) polyester samples

Table II shows that a 6th degree polynomial curve fitting presents residuals as low as ~2.3%, ~2.5%, ~1.2% respectively for A15, J4, C15 samples, in comparison to a "simple" linear approximation. A polynomial higher than six degree does not produce meaningful advantages. Anyway, the 6th degree polynomial claims the sensor to be subjected to a time-expensive calibration procedure before its usage, since it is necessary to bend it at six different angles and acquiring the relative resistance values to obtain the six coefficients of the equation.

TABLE II. RESIDUALS WITH RESPECT TO THE EQUATION DEGREE

Equation degree	**Residuals**		
	A15	***J4***	***C15***
1st	54909	40757	28134
2nd	13240	10875	9129
3rd	4186	4367	5734
4th	3405	3863	2121
5th	2232	1220	1300
6th	1262	1014	345
7th	1127	983	310
8th	1115	882	275
9th	1012	871	176
10th	957	871	172

A convenient alternative can be to consider a step-wise linearization: a linear fitting within 0°-40° range and another linear fitting within 40°-120° range. In such a manner, the angle range versus R^2 couples "Δα;R^2" are:

- sample A15: "0°-40°; 0.8275" and "40°-120°;0.9962"
- sample J4: "0°-40°;0.7878" and "40°-120°;0.9963"
- sample C15: "0°-40°; 0.7977" and "40-120°;0.9929"

Although these results are obtained for special cases (in particular for FP uncoated, polyester-coated and polyamide-coated 2" RFS samples), the same results can be usefully generalized for any FP RFSs, because of the possibility of normalization already discussed.

When the non-linearity can be a relevant issue, linearization procedures ca be adopted, such as to insert a standard fixed-value resistor in parallel to the RFS under test [11], or to cut the RFS in a shape different from the standard rectangular one [12] or, finally, to add a coating layer [11], but waiving to the advantage of the greater sensitivity and, in fact, turning to the coated occurrence.

Differently from the FP RFSs, the SS ones demonstrate an inner high degree of linearity (R^2=0.997), as shown in Figure 7.

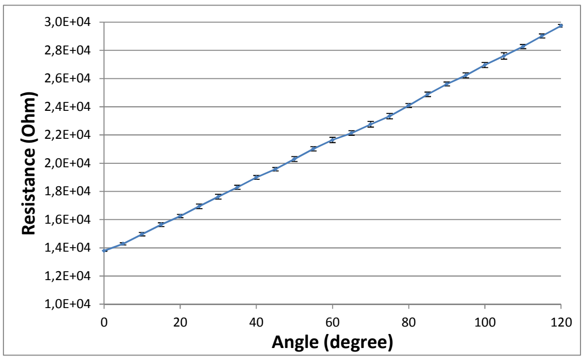


Figure 7. The SpecrtaSymbol RFSs demonstrate an inner high degree of linearity of the "*R* vs. *α*" curve.

In a previous work a mechanical model of the RFSs was developed to demonstrate that isotropy, of both the supporting layer and the on-top engineered sensible material, claims linearity of the "*R* vs. *α*" curve [13]. That demonstration suggests that FP RFSs are made of anisotropy elements and that SS RFSs have isotropy body. Another hypothesis for the linearity of the SS RFSs can result from the added metallic pads. In fact, as reported in [11], one method to linearize a non-linear behavior of an RFS is to add a parallel resistance and those pads can similarly "operate" as a sort a current-divider resistor.

B. Sensitivity

The FP polyamide-coated, polyester-coated and bare RFSs have higher sensitivity $S=\Delta R/\Delta\alpha$ for angles >40°, >25° and >18° respectively, as reported in Figure 8.

For lower angles the FP RFSs sensitivity is reduces and comparable to the one of the SS RFSs.

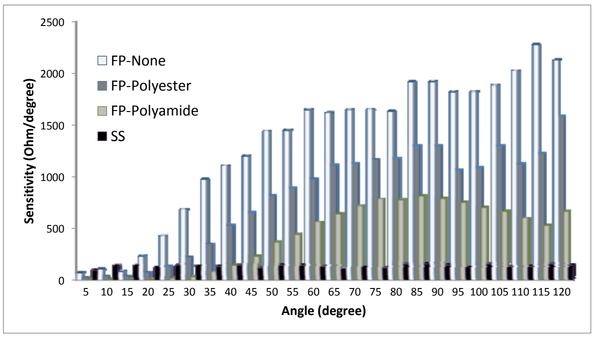


Figure 8. Sensitivity versus bending angle for all types of RFSs

C. Repeatability and hysteresys

Among the specific features of a RFS, it is important that such a sensor can perform without any meaningful variation in measurement when subjected to the same testing conditions, i.e. to offer repeatability. In addition, it is relevant to observe if the resistance value, acquired at the same angle, is maintained when tests are performed when the stepper motor both increases the angle value and lowers the angle values, i.e. if RFS performs without meaningful hysteresis.

All our tests were ten times iterated, and we evaluated the repeatability of the measures in terms of the standard deviation (SD) expressed in percentage. Figure 9 summarizes the obtained results.

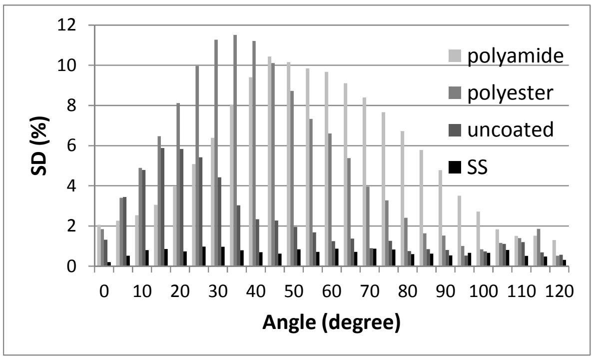


Figure 9. SD(%) versus bending angle for all types of RFSs

It can be evidenced that a lower, and practically constant SD(%) results for the SS RFSs at all the tested angles. The FP RFSs perform with higher SD(%) in particular for middle angles, and the coated versions perform with higher SD(%), therefore a lower repeatability.

Regarding the hysteresis, all RFSs performed with values lower than the respective SD, so that we can affirm that it is practically irrelevant.

D. R vs. pin radius

The resistance variation in bending a RFS is necessarily proportional to the portion of its length effectively flexed. Therefore, it is reasonable to experience higher resistance variation for lower value in diameter of the pin of the hinge. Figure 10 reports the resistance trend for the special case of

 ISBN: 978-1-61208-523-4

the FP RFS B11 sample with different pins of 0.6, 0.8, 1.0 and 1.2cm in diameter. Although this is just an example, we experienced the same trend for all our FP RFSs samples.

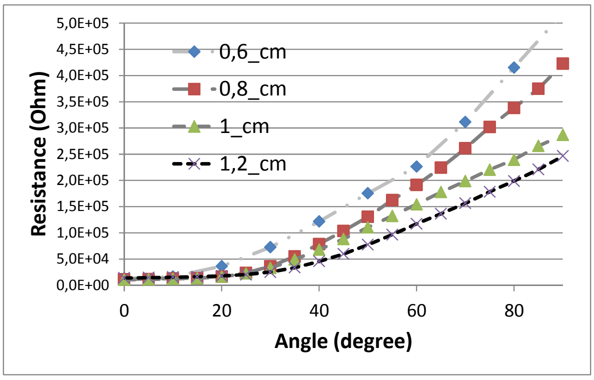


Figure 10. Comparison of resistance variation trends of the FP B11 sample when flexed around pins with different diameter

E. *Different coatings*

An additional layer, on-top of the conductive one, can help in mechanical protection and increase the possible cycle of bending mechanical stress before failures of the sensor. This is why some types of RFSs come with some coatings, in particular made of polyester or polyamide. However, the advantages resulted from a mechanical point of view affect the sensors electrical performances. In particular, our tests evidenced a reduction in the range (max-min) of resistance variation, more evident with the polyamide coating with respect the polyester one, as evidenced in Table III. Regarding the SS RFSs, those sensors resulted with the lower range, possibly due to the metallic pads, since there is no evidence of a coating.

TABLE III. COMPARISON OF MIN, MAX AND RANGE OF AVERAGE RESISTANCE VALUES OF DIFFERENT RFSS

RFS type	**Resistance**		
	min	***max***	***range***
FP uncoated	6839	257756	250917
FP polyester	6279	107904	101625
FP polyamide	9605	74124	64519
SpectraSymbol	13783	29750	15967

Again, also in spite of the coating layer, the FP RFSs result with the same trend in "*R* vs. α" curves, as evidenced in Figure 11 reporting the normalizing resistance data to 0-1 range.

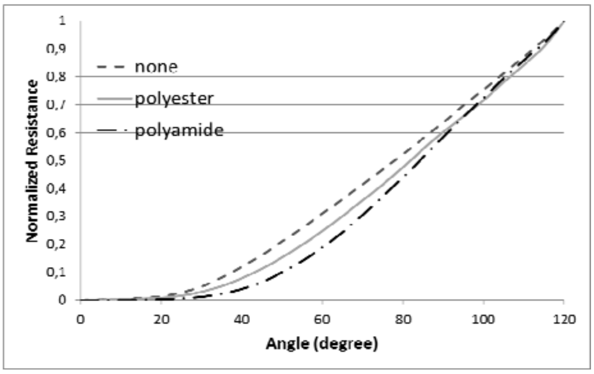


Figure 11. Normalized resistance versus bending angle for FP RFSs differently over-laminated.

F. *Inward bending*

For completeness, in addition to the outward bending (that is the bending which "elongates" the sensible conductive layer), we performed the inward bending, in particular from 0° to -90°, 5° stepped, averaging data of ten iterations. As it can be expected, results demonstrated the uselessness of RFSs in inward flexion. As an example, Figure 12 reports the behavior of the C1 (polyester-coated 3" long) FP RFS sample.

This figure reports a non-monotonic function, which leads to the impossibility to determine unequivocally a bending angle from the reading of the resistance of the sensor. In addition, Figure 12 shows an inconsistent repeatability of the measure, since we obtained meaningful standard deviations (SDs), in particular for angle of bending within the -70° and 0° interval.

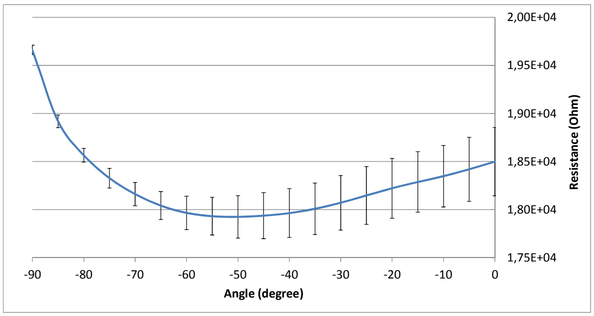


Figure 12. How FP C1 sample behves in inward bending. Vertical lines evidence high value of SD

G. *Step Response Decay*

A common requirement for any sensor is that its response has to be always the same with unchanging boundary conditions. In addition, a time-independent sensor has to maintain its response unchanged over time. In order to evaluate this characteristic for our RFSs, we tested their *step response decay* (a variation in resistance over time after a step transition to a different bending angle).

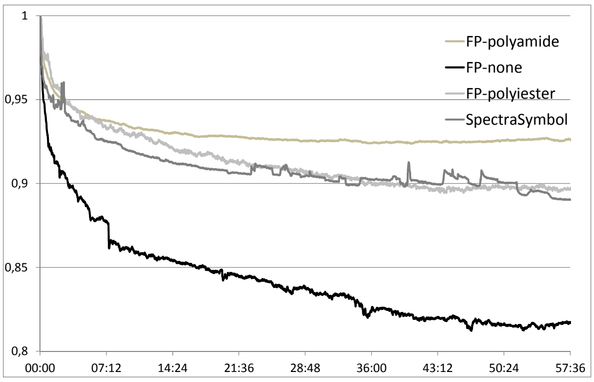


Figure 13. Step response decay, during 60min, for all RFSs under test.

Figure 13 reports the obtained results.

Approximately 15 mins are necessary for the FP polyamide-coated, for the FP polyester-coated and for the SS RFSs to gain a roughly stable value of resistance, respectively equal to the 93%, 90% and 90% of their initial value; a triple time (45mins) occurs for the FP bare RFS to reach some stability in resistance equal to the 82% of the initial value. These results are comparable to the ones obtained in [14], and suggest that it is fundamental to always establish the same acquisition time after each bending of the sensors.

IV. Conclusions

The choice of the right RFS is strictly related to the application.

The FP RFSs offer high sensitivity but low linearity within all the tested bending range (0°-120°). Such sensors are well exploited when connected to a low-gain non-linear amplifier. The fact that FP RFSs with the same characteristics (equal length and coating) behave differently, force the user to perform tests before their usage or, alternatively, to count on the normalized resistance values rather than the actual ones.

The coating reduces the sensitivity of the sensors, so that it can be recommended to use a coated sensor when strictly necessary, for example when RFSs have to be used in a harsh environment.

The SS RFSs offer high linearity but low sensitivity, so that are well exploited when connected to a high-gain linear amplifier. In addition, SS RFSs of the same type (here a unique one) behaves with the same resistance values, so that we can perform a unique test before their utilization.

High and acceptable repeatability of measurements was demonstrated for SS and FP RFSs respectively, and, for all RFSs, the importance to establish and maintain a time cadence in acquiring the measures to overcome issues related to the not-negligible step response decay.

All considering, the commercial RFSs we tested are suitable to be generally adopted as bending sensors.

Acknowledgment

This paper was partially based on a work supported by the Italian Space Agency (ASI), contract #2013-081-R0, for which we would like to thank Prof. Mariano Bizzarri, Dr. Simona Zoffoli and Dr. Francesca Ferranti.

References

[1] G. Orengo, A. Lagati, G. Saggio, G. “Modeling Wearable Bend Sensor Behavior for Human Motion Capture.” IEEE Sensors Journal, Volume: 14 , Issue: 7, pp. 2307 – 2316, 2014

[2] G. Saggio, F. Riillo, L. Sbernini, L . R. Quitadamo “Resistive flex sensors: a survey.” Smart Materials and Structures, Volume 25, Number 1, pp. 1-30, 2016

[3] A. S. Evani, B. Sreenivasan, S. S. Joshi, M. Prakash, and J. Bapat, “Activity Recognition Using Wearable Sensors for Healthcare.” In: The Seventh International Conference on Sensor Technologies and Applications, (Barcelona) pp 173-7, 2013

[4] D. A. Kingsley, R. D. Quinn and R. E. Ritzmann, “A cockroach inspired robot with artificial muscles.” In: IEEE/RSJ International Conference on Intelligent Robots and Systems, (Beijing, China), pp 1837-42, 2006

[5] L. X. Ng, S. W. Oon, S. K. Ong and A. Y. C. Nee, “GARDE: a gesture-based augmented reality design evaluation system,” International Journal on Interactive Design and Manufacturing (IJIDeM) 5 pp. 85-94, 2011

[6] L. Persson “Bältespåminnelse-system för baksäte: inventering och utvärdering.” University West, Department of Technology, 2002

[7] L. C. Hau and K. D. Kincaid, “Method and apparatus for detecting a pedestrian impact.” (Google Patents), 2008

[8] A. Mulder “Getting a GRIP on alternate controllers: Addressing the variability of gestural expression in musical instrument design” Leonardo music journal 6 pp. 33-40, 1996

[9] J. Bukhari, M. Rehman, S. I. Malik, A. M. Kamboh and A. Salman “American Sign Language Translation through Sensory Glove.” SignSpeak International Journal of u-and e-Service, Science and Technology 8 pp. 131-42, 2015

[10] http://www.nicomatic.co.uk/pages/products/conductive%20compounds/c100.htm

[11] R. Gentner and J. Classen “Development and evaluation of a low-cost sensor glove for assessment of human finger movements” Neurophysiological settings Journal of neuroscience methods. pp. 178 138-47, 2009

[12] G. Orengo, A. Lagati, G. Saggio, “Bend Sensors Modeling for Fast Signal Recovering in Human Motion Analysis” The 3rd International Conference on Sensor Device Technologies and Applications, pp. 21-24, 2012

[13] G. Saggio “Mechanical model of flex sensors used to sense finger movements”, Sensors and Actuators A 185, pp. 53– 58, 2012

[14] N. P. Oess, J. Wanek and A. Curt “Design and evaluation of a low-cost instrumented glove for hand function assessment” Journal of neuroengineering and rehabilitation, 2012